Abstract—In this paper, an enhanced access protocol minimizing message delivering latency is proposed. It is basically based on modified version of Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol in which one sensor at a time is allowed to deviate from standard rules behaving like a cheater and keeping the Contention Window (CW) fixed and equal to the minimum value. The proposed scheme efficiency is proved resorting to game theoretic framework, while its performance is analytically derived through a Markov model for a worst case conditions. Focusing on Wireless Body Area Networks (WBANs) application scenario, main system figures, in terms of delivering delay and dropping probability, are further pointed out by means of numerical simulations, highlighting optimal agreement with theoretical results as well as the protocol suitability for critical situation management.

Index Terms—Medium Access Control protocols, Delivering Latency Minimization, Game Theory, Markov Model.

I. INTRODUCTION

Wireless Sensor Networks (WSNs) rapidly imposed as an innovative paradigm for everyday life applications. They are basically comprised of several nodes capable of sensing or interacting with the surrounding environment however with a limited scope due to their intrinsic constraint in term of cost and complexity. In order to achieve efficiency as a whole, data exchange among nodes is needed to refine partial information and to coordinate intervention and control.

WSN principle has been recently applied to e-health (including patients remote monitoring, rehabilitation or even care) and to e-wellness (virtual trainers, performance logger) requiring that sensors might be worn ed or even in body implanted. Specifically, this novel research area, referred to as Wireless Body Area Networks (WBANs), is deeply investigated for enormous potential benefits it is able to provide in terms of cost reduction of public health system. For instance, the automatic and continuous monitoring of chronic diseases could be effectively performed cutting unnecessary pharmacological treatment. Up to now, it has not been yet defined a comprehensive standard for WBANs, but starting from November 2007, IEEE formed a working group called IEEE 802.15.6 to address this issue. Present prototypes or commercial products are instead based on existing IEEE 802.15.4 standard.

A typical WBAN scenario is composed of sensor directly communicating with a coordinator performing data aggregation and processing. As soon a critical situation is detected, a warning or an alarm message is sent by interested sensors to the remote coordination center in charge of planning the successive intervention1. Clearly a crucial aspect is represented by the minimization of the delivering latency; in particular, it is often enough to receive one message as it is supposed that heterogeneous sensed data are highly correlated.

The present proposal is concerned with the Game Theory (GT) application to the aforementioned case study, since it can be conveniently modeled as a game occurring among rational and selfish players, i.e., which try to maximize their payoff disregarding the others’ utilities. In particular, we focus on a modified Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol in which one sensor at a time is allowed to deviate from standard rules behaving like a cheater and keeping the Contention Window (CW) fixed and equal to the minimum value2.

The paper is organized as it follows: in Sect. II the proposed scheme is introduced, adequately motivating its applications to a reference scenario and pointing out the gap in the existing literature in terms of provided quality of service (QoS) parameters. Further, a Markovian analytical model to derive the system performance is introduced in Sect. III, while it is validated through numerical simulations conducted over realistic scenarios in Sect. IV. Finally, some conclusion are drown together with indicating possible enhancements.

II. PROPOSED MAC PROTOCOLS FOR WBANs

A. Motivations

Although IEEE 802.15.4 [1] standard has been widely adopted for WSN typical applications, the extension toward WBANs dictates, however, additional constraints especially for warnings/alarm dispatching in terms of accuracy, latency and security issues. As a matter of fact, in beacon-enabled operation mode, channel access is arbitrated by CSMA/CA protocol [] which does not manage differentiated flows with specific QoS constraints 3.

The reference scenario is composed of a cluster of sensors each monitoring a specific vital parameter related to overall health condition 4, and wirelessly transmit sensing to the coordinator 5.

1In this case the bursty traffic profile make the network to operate in saturation regime.
2In this case we adopted a non cooperative static game model.
3It happens, in particular, in case of time critical events related to teleassisting or telemonitoring applications.
4It could be the case of multi-leads ECG integrating information on body temperature, blood-oxygen level, heart rate variability, and even blood pressure.
parameter adopting a low power duty cycled approach, thus out in Fig. 2 in a decreasing order [3]: the following classes, according to traffic features, as pointed different devices. Foreseen applications has been divided into model for mittee [2], that, presently, is developing a complete layered WBANs applications, it has been created IEEE 1073 com-

B. Reference Scenario

With the aim of defining universal requirements for biomedical WBANs applications, it has been created IEEE 1073 committee [2], that, presently, is developing a complete layered model for medical information bus allowing interoperability of different devices. Foreseen applications has been divided into the following classes, according to traffic features, as pointed out in Fig. 2 in a decreasing order [3]:

1) Real time low data rate, mainly related to system monitoring and control;
2) Best-effort low data rate, e.g. electromyographic (EMG) and endoscopic sensing with up to 3 sensors;
3) Real time high data rate, including electroencephalogram (EEG), electrocardiogram (EGC), blood analysis [4], typically with 10 to 20 sensors.

Each biosensor usually samples a specific physiologic parameter adopting a low power duty cycled approach, thus sending information to its coordinator whenever a critical situation is detected (usually with a threshold criterion) with a maximum bit rate of 10 kbps. As a consequence, typical monitoring scenarios request an overall bandwidth lower than 500 kbps.

Focusing on time sensitive applications, we hereinafter refer to an ECG monitoring performed with a cluster of highly correlated sensors to evaluate the alarm delivering latency. According to IEEE 1073 [5] each sensor need 4 kbps, while the overall transmission and processing latency is around 500 ms [6].

C. State of the Art

Current standards supporting WBSN applications can provide only best effort services which are inadequate for life critical and emergency applications, whose common QoS end-to-end constraints involve available throughput, packet delivery rate and jitter. For instance, the widely known CSMA/CA scheme adopted in IEEE 802.15.4 compliant devices [7], does not allow any traffic differentiation as it assigns by default the same access parameter whatever the node was.

In November 2007, IEEE 802.15 Task Group 6 (BAN) has been introduced to define comprehensive guidelines for a future WBANs standard involving low power wearable/implantable devices. It has been addressed that MAC protocols design plays a key role for providing efficient medical applications and this topic is currently under investigation. The adoption of WSN typical approaches seems to be really unsuited as:

- WBANs nodes are more resource constrained than WSNs’ and redundant deployment can not be afforded to limit invasiveness;
- typical applications concern real time continuous monitoring associated with high priority alarm dispatching which dramatically impact on QoS profiles.

Some efforts have been spent to provide IEEE 802.15.4 standard with differentiated traffic classes management [8]. In [9] it has been proposed a slotted CSMA/CA mechanism with services differentiation within Contention Access Parameter (CAP) subframe. Two classes have been introduced with different default values for the Contention Window (CW) parameter of exponential backoff algorithm; in particular, \( CW = 1 \) for high priority flows, while \( CW = 2 \) for low priority ones. In addition an analytical Markovian model has been derived for non saturated regime to evaluate the throughput performance for single collision domain scenario. Although different performance figures are achieved, this approach is not convenient to our purposes, since priorities are a priori and statically allocated, while in medical monitoring node priority is correlated to critical situation which can greatly varies over time and it is sufficient to deliver one alarm.

6 Additional requirements might involve also scalability, robustness and fault tolerance.

7 To cope with these impairments IEEE 802.11 standard introduced IEEE 802.11e/f/i amendments to enhance QoS, interoperability and security issues, respectively.
A promising approach is represented by Game Theory (GT) even though existing literature is focused on throughput optimization for IEEE 802.11 systems. One pioneering work [10] discusses Nash equilibria for slotted ALOHA scheme and optimizes access probability to achieve the best throughput (representing the player payoff) under the hypothesis of perfect information. Concerning CSMA/CA protocol, in [11] it is preliminary shown that exponential backoff introduces a certain degree of cooperation among nodes only for repeated games. Moreover, [12] underlines that generally speaking the presence of selfish or malicious nodes make the protocol to be unfair. Finally, CSMA/CA scheme performance in the presence of cheats is preliminary shown in [13]. Adopted strategy consists in keeping fixed the CW size instead of following the usual exponential increment. Two Nash equilibria families are derived, one leading to the so called tragedy of commons for what throughput is concerned.

III. ANALYTICAL MODEL

A. Slotted CSMA/CA Model

The present analysis generalizes the Markov model presented in [14], originally conceived for IEEE 802.11 saturated throughput, toward derivation of message delivering delay upper bound in the case of IEEE 802.15.4 system. It has been assumed that all the nodes strictly follows the standard algorithm [15]. As a consequence, the following parameters have to be taken into account:

- Contention Window (CW), whose initial value is equal to 2;
- macMinBE: minimum value for the backoff exponent equal to 3;
- aMaxBE: minimum value for the backoff exponent equal to 3;
- macMaxBackoffPeriod: maximum number of transmission attempt equal to 5.

The bidimensional Markov chain is sketched in Figure 3, whose generic status \((i, j)\) with \(i = \{0, 1, 2, 3, 4, 5\}\) depends on current BE, while \(j = \{0, 1, 2\}\) denotes the CW actual value. Once the initialization phase (INIT) is terminated it is assumed that there is at least one packet in the transmitter queue\(^7\), then the state \((i, j) \leftarrow (0, 2)\) is entered; if the channel is detected idle (with probability \(1 - p\)), it occurs the transition \((i, j) \rightarrow (i + 1, j)\) implying the decrement of CW. Whenever CW = 0 packet is successfully delivered and system promptly evolves toward INIT state.

Conversely, if the channel is detected to be busy (with probability \(p\)) it happens the transition \((i, j) \rightarrow (i, j - 1)\) implying the decrement of CW and the increment of NB. Once NB reaches its maximum value (denoted as \(M\)), an additional collision make the packet to be definitively dropped.

\(^7\)It means a node not following the standard rules.

The average delay related to the \(i\)-th step of the algorithm is equal to:

\[
\delta_i = \frac{(2^{2i} a - 1)}{2}, \quad 0 \leq i \leq M
\]

whose maximum value is reached as \(i\) is equal to \(aMaxBE\) (vz. \(M\)).

It is easy to derive the state probability \(P(i, j)\) as it follows:

\[
P(i, 1) = (1 - p)P(i, 2), \quad 0 \leq i < M, \quad M = 5 \quad (2)
\]

\[
P(i, 2) = [P(i - 1, 2) + P(i - 1, 1)] \quad 1 \leq i < M \quad (3)
\]

\[
P(M, 2)(1 - p) = [P(M - 1, 1) + P(M - 1, 2)]p \quad (4)
\]

\[
P(M, 1)(1 - p) = P(M, 2)(1 - p) \Rightarrow P(M, 1) = P(M, 2) \quad (5)
\]

By averaging over possible states (i.e., \(0 \leq i \leq M\)) the mean delay \(\delta\) becomes:

\[
\bar{\delta} = \frac{1}{T} \sum_{i=0}^{M} \pi_i \delta_i
\]

while the normalized delay \(\bar{\delta}\) is:

\[
\bar{\delta} = \sum_{i=0}^{M} \pi_i \delta_i
\]

In Fig. 4 the state probabilities \(P_k = P(i, j)\), where \(k = 0, 1, ..., 12\) are pointed out as a function of collision probability \(p\). It is worth noticing that \(P_k (K \leq 11)\) is monotonically decreasing, while the converse is true for \(P_{12}\). Further the mean normalized delay and dropping probability are investigated, respectively, in Fig.s 5 and 6 as a function of number of sensor \(N\). Not surprisingly, delivering delay decreases as \(N > 10\) since dropping probability increases and discarded packets give no contribution to latency estimation. Finally, the collision probability again as a function of number of nodes is presented in Fig. 7, pointing out it is reasonably low for \(N < 10\).

\(^8\)The saturation hypothesis has been assumed to model the a critical worst case scenario in which many sensors are trying to send an alarm.
B. Single Cheater Scenario

To allow the real-time message delivering at least for one sensor, it has been introduced a cheater node who is allowed to keep BE parameter fixed and equal to minimum value 3. The introduction of one cheater ($C = 1$) does not affect the access probability $\tau$ regarding both cheater ($\tau_C$) as well as the remaining $N - 1$ well-behaving nodes ($\tau_1$) if and only if $N >> 1$ and $C << N$. As a consequence, also collision probability $p$ remains unchanged according to Eq. 6. Also the access delay for well-behaving nodes does not vary (Eq. 7), while it is obviously reduced for cheater node:

$$\pi_i \delta_i = \sum_{j=0}^{i-1} \left( \frac{2BE_0 - 1}{2} \right) Tp^j (1 - p)^j + \sum_{j=1}^{i} j(1 - p)^j$$

$$0 \leq i \leq M$$ (10)

where the initial BE value (i.e., $BE_0$) is equal to $\text{macMinBE}$ (i.e., 3). This, in fact, represents the minimum delivery delay as it will be further clarified, and the introduction of more than one cheater is not able to bring additional benefits.

C. Multi Cheater Scenario

The previous analysis can be generalized toward the case in which $C > 1$, that is more than one sensor could behave as Cheater. Basing on theoretical results originally provided in [13] for IEEE 802.11 MAC protocol, we derive two classes of possible Nash equilibria.

Let introduce the following notation:

- $N$: number of player, $C$ of whom are cheaters ($C \leq N$);
- $W_i$: fixed contention window (CW) of $i$-th player, $W_i = 1, \ldots, W_{\text{max}}$ (i.e., its strategy);
- $\tau_i$: access probability of $i$-th player (saturation regime);
- $r_i$: average throughput of $i$-th player, representing also its utility function (i.e., $U_i = r_i$);
- $W = \{W_1, \ldots, W_C\}$: the strategy profile of all players.

Resorting to the classic model [14], we introduce two different access probabilities: $\tau_i^l$ for the $i$-th player respecting the CSMA/CA rule and $\tau_i^c$ for a cheater, who does not vary its CW $W_i$. As a result, it follows that:

$$\tau_i = \frac{2}{W_i + 1}$$ (11)

It is possible to prove the following propositions [13]:

Fig. 3. Catena di Markov per l’algoritmo CSMA/CA slotted

Fig. 4. State probability as a function of collision probability.

Fig. 5. Mean normalized delay as a function of number of nodes.

Fig. 6. Dropping probability as a function of number of nodes.

Fig. 7. Collision probability as a function of number of nodes.
Lemma 3.1: For each strategy profile W = \{W_1, \ldots, W_C\} forming a Nash equilibrium \( \exists i \) t.c \( W_i = 1 \).

Lemma 3.2: A static game admits \( W_{\text{max}} - (W_{\text{max}} - 1)^C \) Nash equilibria.

By combining Lemma (3.2) with (3.1), it yields that, given a generic Nash equilibrium, there exists at least one player with CW equal to 1, while CW is greater than 1 for the remaining ones. Thus, defining \( D = \{i : W_i = 1, i = 1, \ldots, C\} \), all equilibria can be partitioned in two sets:

- \(|D| = 1\): there is only one node (let be the \( i\)-th player) with \( W_i = 1 \) and a throughput \( r_i > 0 \), while for the other nodes \( r_j = 0, j \neq i\);
- \(|D| > 1\): in this case, \( W_i = 1 \) for \( i = 1, \ldots, C \) but \( r_i = 0 \), leading to the so called tragedy of the commons.

The, the only way to achieve a satisfactory utility is to allow only one player at a time to behave as cheater. This can be easily generalized toward the scenario under investigation by introducing the following:

Lemma 3.3 (duality): Packet delivering delay \( \delta \) is in inverse proportion to useful throughput \( r \).

Proof:

In a contention based channel access scheme, throughput can be roughly approximated as:

\[
r \propto B_u = \frac{B}{nN} \tag{12}
\]

where \( B \) and \( B_u \) represent the available and useful bandwidth, respectively, \( n \) the channel access attempts and \( N \) the number of users. On the other hand, it is straight forward to show that:

\[
\delta \propto n\theta \tag{13}
\]

where \( \theta \) is the time spent in channel detection and packet transmission. As a result, we have that:

\[
\delta \propto \frac{B}{rn} \theta \Rightarrow \delta \propto \frac{1}{r} \tag{14}
\]

Assuming the following payoff:

\[
\hat{U}_i = \frac{1}{\delta_i} - \frac{1}{\delta_{\text{min}}}.
\]

it is possible to argue the following:

Corollary 3.4: As soon as there exist more than one cheater \( (C > 1) \), \( \hat{U}_i, 0 \leq i \leq N \) becomes null, and, consequently, \( \delta_i = \delta_{\text{max}}, i = 1, \ldots, C \).

In other words, the presence of more than one node keeping fixed its CW, makes the delivering delay to be unbounded\(^{10}\).

IV. NUMERICAL RESULTS

The performance evaluation of the proposed approach has been performed via a simulation campaign conducted within OMNeT++/Mobility Framework tool which properly models IEEE 802.15.4 standard as well as a specific WSN node (CC2420). It has been investigated both a low loaded \( (\rho \approx 0.1) \) or saturated \( (\rho \approx 1) \) regime, with 5 different medical scenarios, as sketched in Tables I-II. For each scenario, the average alarm delivery latency has been evaluated in case a cheater is present or not, together with the packet dropping probability.

The average delay \( \hat{\delta} \) in the presence of one cheater \((C1)\) or not \((C0)\) for both a low and high loaded condition has been pointed out in Fig. 8. It is possible to underline the remarkable latency reduction experienced by the cheater, which is unaffected by the number of nodes. Moreover, latency is slightly decreasing at the increasing of load factor \( \rho \); this is due to the increasing of dropping probability \( P_{\text{drop}} \) which makes the average delay to be evaluated over packet effectively delivered.

To address also this aspect, \( P_{\text{drop}} \) has been depicted in Fig. 9 for all possible operative conditions. Even though this parameter is generically increasing with the number of nodes, however a cheater does not take advantage of a fixed (minimum) CW in low loaded regime, as it is likely that the remaining nodes succeed in delivering a packet and often contend with the same \( BE \) value. Conversely, as \( \rho \rightarrow 1 \) cheater node achieve a gain over the remaining ones.

For the sake of completeness, theoretical and numerical values of \( P_{\text{drop}} \) have been compared in Fig. 10 limiting to saturated conditions., highlighting a good agreement which validate the analytical approach adopted.

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\(^{10}\)It means that either it approaches infinite or the maximum delay tolerated.
V. CONCLUSIONS

In this paper, an enhanced access protocol minimizing message delivering latency is proposed, focusing on WBANs application scenario. It is basically based on modified version of CSMA/CA protocol in which one sensor at a time is allowed to keep the CW fixed and equal to the minimum value. The proposed scheme efficiency is proved resorting to game theoretic framework, while its performance is analytically derived through a Markov model for a worst case conditions. Moreover, the main system figures, in terms of delivering delay and dropping probability, are further pointed out by means of numerical simulations, highlighting optimal agreement with theoretical results as well as the protocol suitability for critical situation management.

A possible enhancement of the proposed approach could consist in dynamically selecting the cheater node for a limited time interval, according to a token passing mechanism, or to a priority aging scheme.

ACKNOWLEDGMENT

This work was supported in part by the Italian National Project “Wireless multiPlatForm MIMO active access network for QoS-demanding multimedia Delivery (WORLD)”, under grant number 2007R989S.

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